Massachusetts Institute of Technology
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Luminary Memo # 208

TO: Distribution

FROM: Allan Klumpp

DATE: March 16, 1971

SUBJECT: Apollo 14 Descent Simulation Dispersions: Terrain Model Mismatch Aggravates Drooping Trajectories in P64 and Low Descent Rate in P66.

SUMMARY

Six weeks before the Apollo 14 mission, a study was started to determine the causes of certain descent dispersions. When P66 was entered automatically, slow descent rates were observed in many simulations. Descent rates at the start of P64 were observed to be 12 fps higher with terrain and radar (158 fps) than without (146 fps) and the resulting approach phase trajectories with terrain and radar were excessively concave upwards (droopy). The droopiness of the P64 trajectory required a flareout at P64 terminus producing a slow terminal descent rate which was carried over into P66. One simulation – with a combination of an 11,400 ft. downrange dispersion, 1σ dispersions in all other state variables and measurements, and a slow pitchover at the start of P64 – crashed into a hill midway in P64. An identical run except with normal pitchover displayed only 230 ft. clearance to the top of the same hill; the clearance in the nominal error free case was just over 1800 ft. With 1σ downrange error being 1000 ft., this was a 11.4σ case, and it did not cause much concern until two days before the Apollo descent. At this time another simulation with only 4.8σ (4800 ft.) downrange error and no other errors cleared the same hill by only 500 ft.

Several individuals at MSC were advised prior to the Apollo 14 landing of the consequences of downrange navigation errors. However, because a safe clearance (500 ft. altitude) to the peak was maintained for as much as 4.8σ navigation error, no action was taken at MSC.

The apriori terrain model (LGC model) was found to not match the "real" terrain defined by Table IX of Ref. 1. The apriori terrain model was about 500 ft. higher than the real model at 47,000 ft. before the landing site. This caused the LGC to compute that it was coming in too high at the critical time near the end of the braking phase. In an attempt to correct the erroneous altitude error, the LGC caused an excessive downward velocity by the end of the braking phase which caused a drooping approach phase trajectory, a flare-out at the approach phase terminus, and low P66 descent rate. The problem was aggravated by a downrange position error; for any error in excess of about 7000 ft. the LM would crash (see Fig. 2).

Jim Alphin of MPAD reports that this terrain model mismatch was intentional; MSC's terrain people doubted the severity of the Fra Mauro terrain and suggested that any apriori modelling errors reduce the severity, which this particular error did. In addition, in MPAD simulations the error in the apriori model reduced the navigated altitude error and flattened the LPD angle profile. MIT simulations have been made with a corrected apriori model and compared with MIT simulations using the MPAD supplied apriori model. MIT results are the reverse of MPAD results; the terrain model mismatch increases navigated altitude error at the end of the braking phase, and the error persists for the first 20 seconds of the approach phase. In addition, the curve of LPD angle vs. time is not as flat and the persistent vertical error produces a small LPD error. With the corrected apriori model no simulations crashed. Three cases, including the worst case (11,400 ft. downrange error) were tested.

There appears to be substantial disagreement between MIT and MPAD simulations. Evidence, in addition to the above, are the curves of the clearance to the 623 ft. hill whose peak lies 10,139 ft. before the nominal Apollo 14 site. In the Apollo 14 case the MPAD simulation showed the trajectory to be substantially safer than the MIT simulation. With terrain models supplied by MPAD, if the MPAD simulation is in error, the results could be disastrous.

The operation of the LGC program was thoroughly examined. The source of the altitude rate command fetched by P66 was traced and found to be the servicer-computed altitude rate just prior to P66 entry, as intended. P66 was found to control altitude rate to within 0.15 fps of the commanded value. Sample hand calculations were made of the descent guidance equation and of the radar altitude update process. The LGC computations agreed with the hand calculations. No instance of unexplained LGC program behavior was found.

CONCLUSIONS

1. A thorough comparative analysis should be made of the radar and terrain simulations at MIT and MPAD to root out the causes of the discrepancies and to avoid recurrence of potentially dangerous errors in terrain modeling.

2. The apriori terrain model should always lie on or below the real terrain model, particularly during the concluding minute of the braking phase. This was also the recommendation of Ref. 2, page 4.

3. Deletion of the apriori terrain model by verb 68 during the concluding minute of the braking phase would have made the P64 droop worse. This was because the apriori model lay below the landing site during most of this time. In general, trajectory dispersions caused by terrain model mismatch may be aggravated by deleting the apriori model. If the apriori model lies below the landing site, deleting the model will cause the spacecraft to fall. If the model lies above the site, deleting it will cause the spacecraft to rise.

4. The descent trajectory should be designed without considering the effects either of a real terrain or of an apriori terrain model. The apriori terrain model should then be designed to minimize the perturbations on the trajectory. Apriori terrain model errors should not be introduced as a device for shaping the trajectory.

REAL AND APRIORI TERRAIN MODELS

Figure 1 shows the real and apriori terrain models and certain consequences of the errors in the apriori models. The figure describes only the final portion of the descent trajectory, beginning 64 seconds before hi-gate and ending at touchdown.

The curves of Frame 1 of Fig. 1 display the best estimate of the lunar terrain before the Apollo 14 landing site (called the real terrain and identified by X on the figure) and also the MPAD and corrected apriori terrain models. The basis for the corrected model was to make the minimum number of changes (2) in the erasable load to improve the correlation in the range immediately preceding hi-gate.

Figures 1 and 5B show that the errors in the MPAD apriori terrain model have a whiplash effect on the trajectory. Figure 5B shows the entire trajectory, Fig. 1 shows only the last 72,000 ft. Before 50,000 ft. range the MPAD apriori model lies consistently below the real model, driving the LM upwards. From 50,000 ft. to hi-gate the error is reversed; the apriori model lies consistently above the real model driving the LM downward. This whiplash effect is the primary cause of the drooping P64 trajectory and the low descent rate in P66. It has other effects as follows.

The curve of Frame 2 of Fig. 1 verifies that the errors in the two segments preceding hi-gate of the MPAD apriori model produce, by themselves, over 250 ft. of droop in the P64 trajectory.

The curves of Frame 3 of Fig. 1 show that the errors in the MPAD apriori model produce almost 200 ft. more navigated altitude error than the corrected apriori model, and these errors persist well into the approach phase.

The curves of Frame 4 of Fig. 1 show that the LPD angle is not as constant with the MPAD apriori model as with the corrected model. However, the maximum LPD error resulting from navigated altitude error was computed to be only 0.76°.

HILL CLEARANCE VS DOWNRANGE ERROR AND APRIORI TERRAIN MODEL ERROR

It can be seen from Fig. 1 that if the actual landing site and the apriori terrain model are both displaced uprange (short) relative to the nominal landing site and the real terrain, then the terrain model error at the end of the braking phase is increased and the clearance to the 623 ft. high peak midrange in P64 is decreased. Note that a downrange navigation error produces an equal uprange displacement of the landing site and of the apriori terrain model. Several bit-by-bit simulations were run to determine the magnitude of this effect and the influence of the terrain model errors.

Figure 2 shows the influence of downrange displacement of the actual landing site on the clearance to the aforementioned peak and on the altitude rate at the start of P64. Each of the Figures 3 thru 10 shows the trajectory which corresponds to one point on Fig. 2. Figures 3 thru 10 each contain part A, spacecraft and terrain altitude; part B, the real and apriori terrain; and part C, the real and apriori terrain for the approach phase.

The curves of Fig. 2 marked o correspond to Figs. 3 thru 7, and show the influence of downrange displacement of the landing site when using the MPAD supplied apriori model. Note from extrapolating the clearance curve, if the uprange displacement is over about 7000 ft., the LM will crash. Figure 7 shows such a case; with an 11,400 ft. uprange displacement the LM crashed about midway up the hill at 99 fps forward velocity and 62 seconds time remaining in the approach phase.

The effect of the corrected apriori terrain model is indicated by the curve marked ▽ which corresponds to Figs. 8 thru 10. Figure 10 shows that the LM does not crash with the corrected apriori model even with 11,400 uprange displacement of the actual landing site. However, it enters P66 with a positive altitude rate and therefore ascends until fuel depletion.

The curve of Figure 2 marked + was drawn from data supplied by Jim Alphin of MPAD. It shows the same trend as MIT bit-by-bit simulation data, but indicates substantially greater clearance.

The curve of Frame 2 of Fig. 2 provides a method of predicting a dangerous approach phase trajectory; -171 fps altitude rate at the start of P64 corresponds to 7000 ft. uprange displacement of the landing site, the amount beyond which a crash can occur.

Allan R. Klumpp

FIG 1

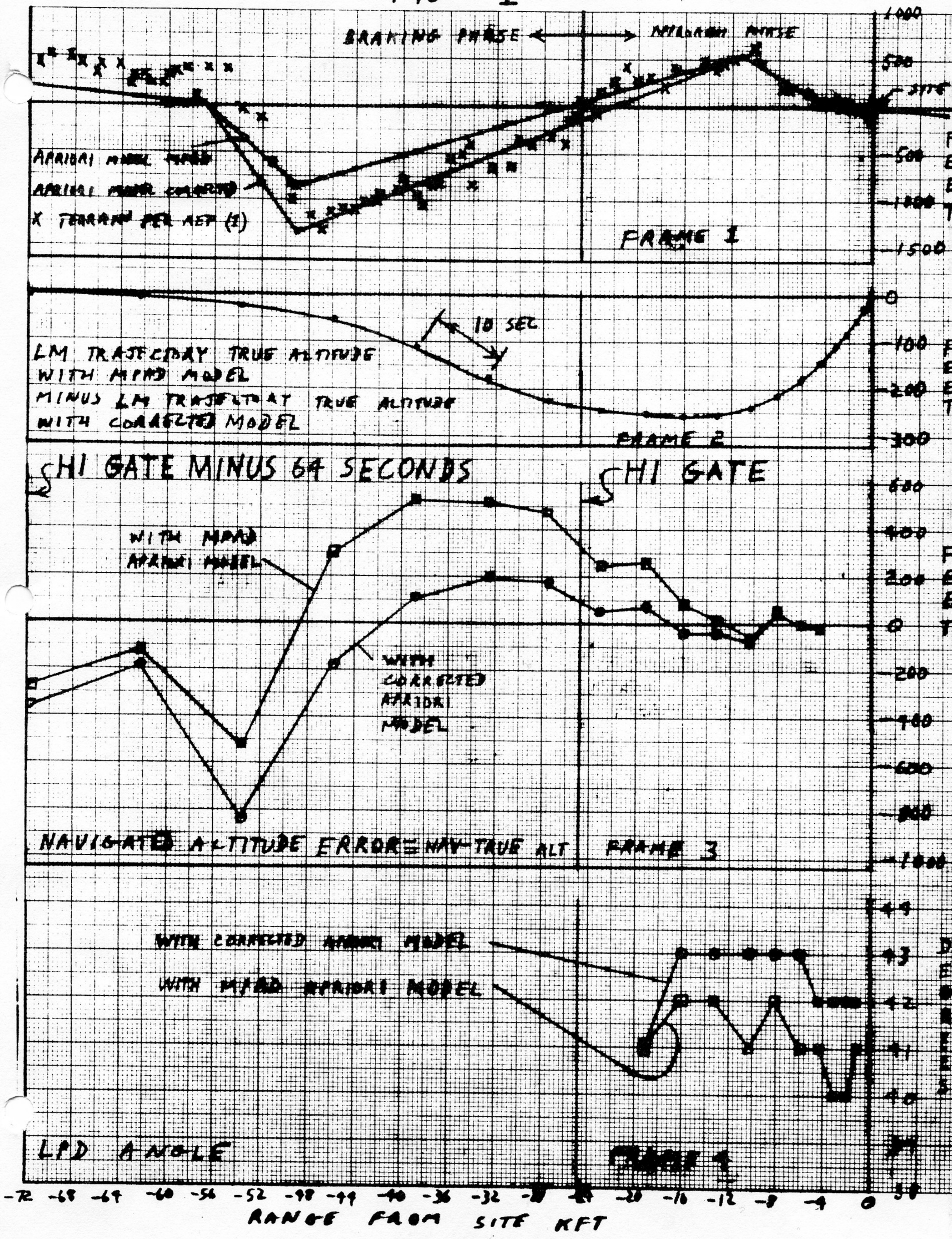

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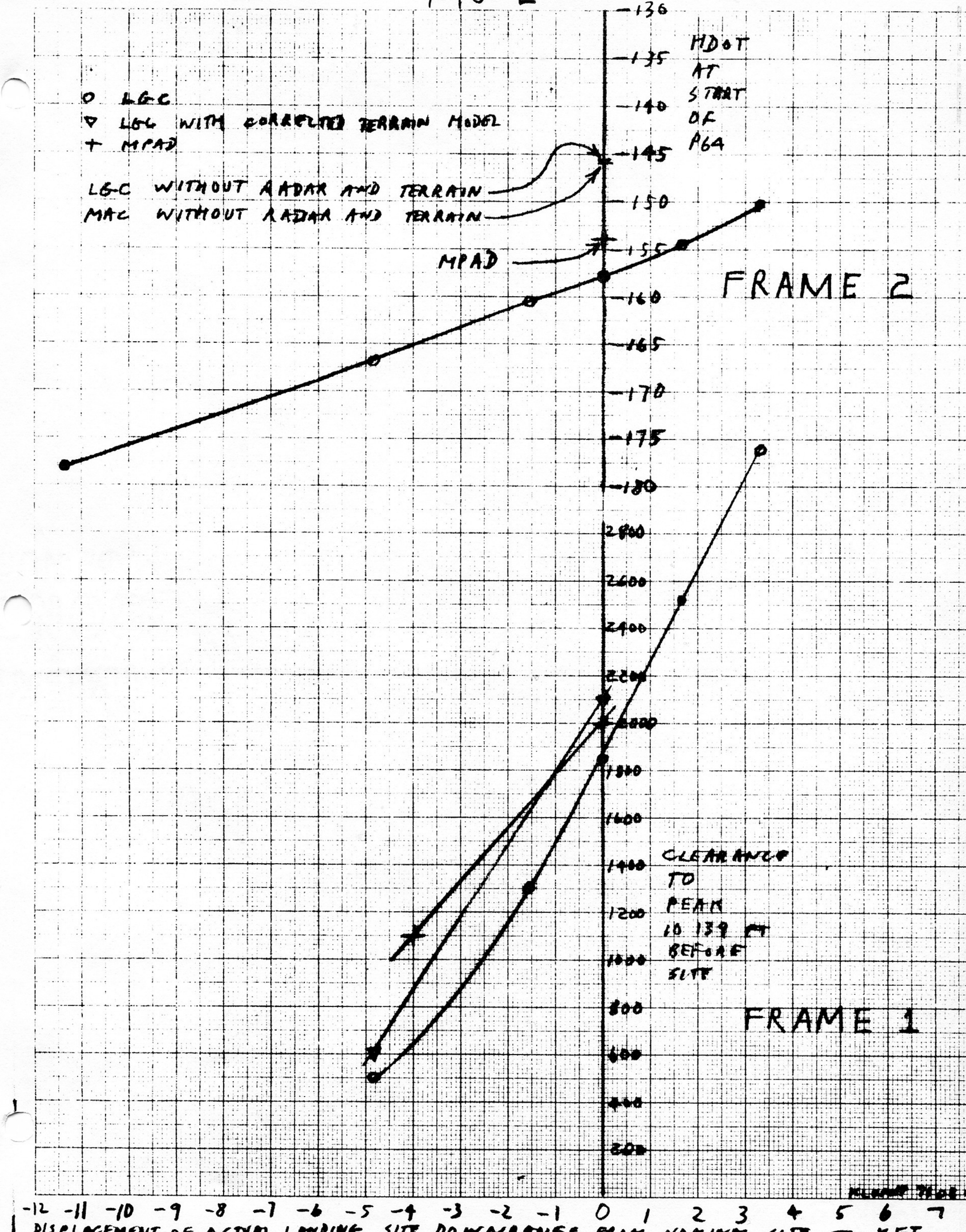
FIG 2


O LGC
▽ LGC WITH CORRECTED TERRAIN MODEL
+ MPAD
LGC WITHOUT RADAR AND TERRAIN
MAC WITHOUT RADAR AND TERRAIN
MPAD
HDOT AT START OF P64
FRAME 2
CLEARANCE TO PEAK 10 139 FT BEFORE SITE
FRAME 1
DISPLACEMENT OF ACTUAL LANDING SITE DOWNRANGE FROM NOMINAL SITE — KFT

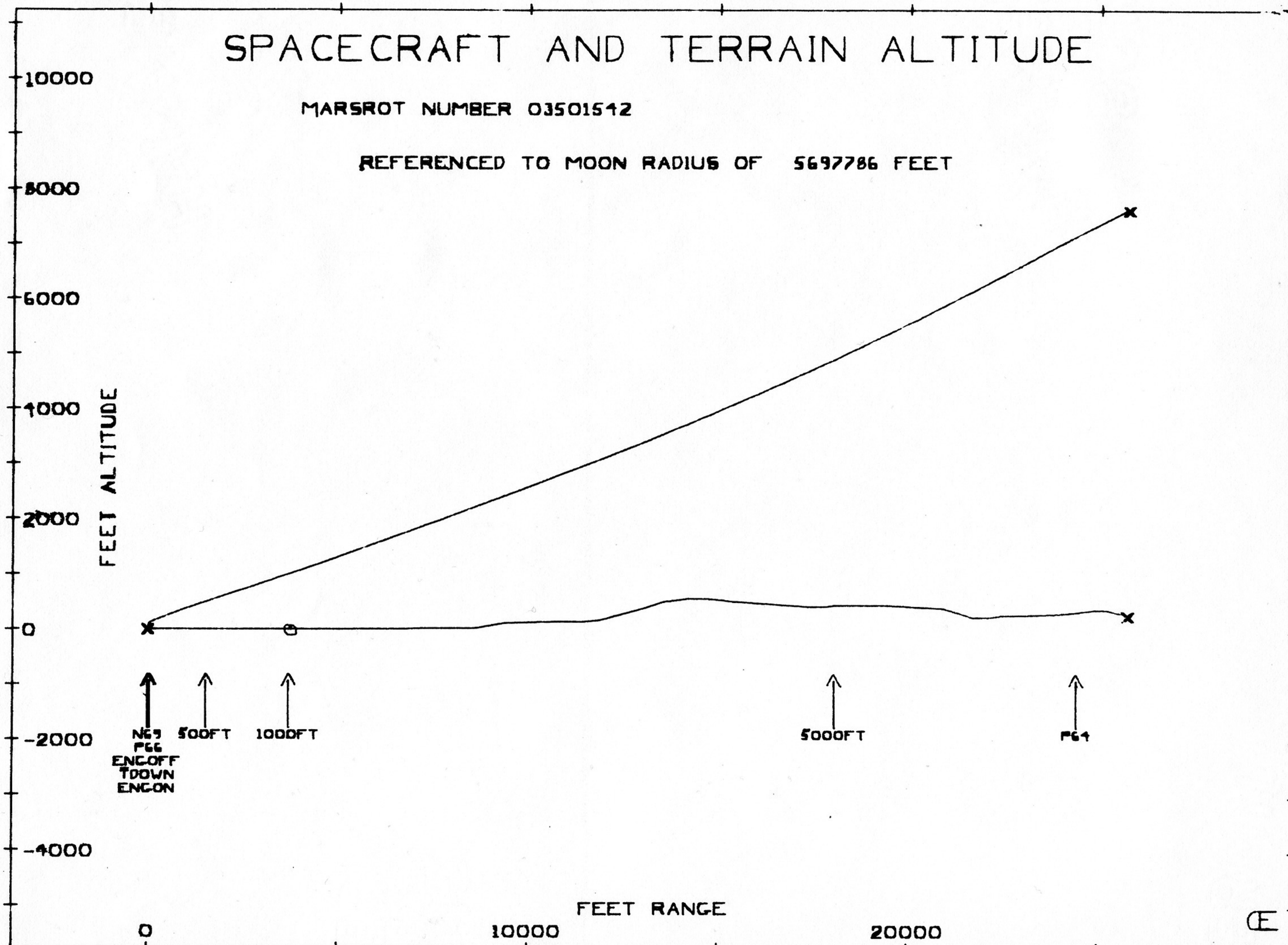


Figure 3A Land 3280 ft. Beyond Nominal Site

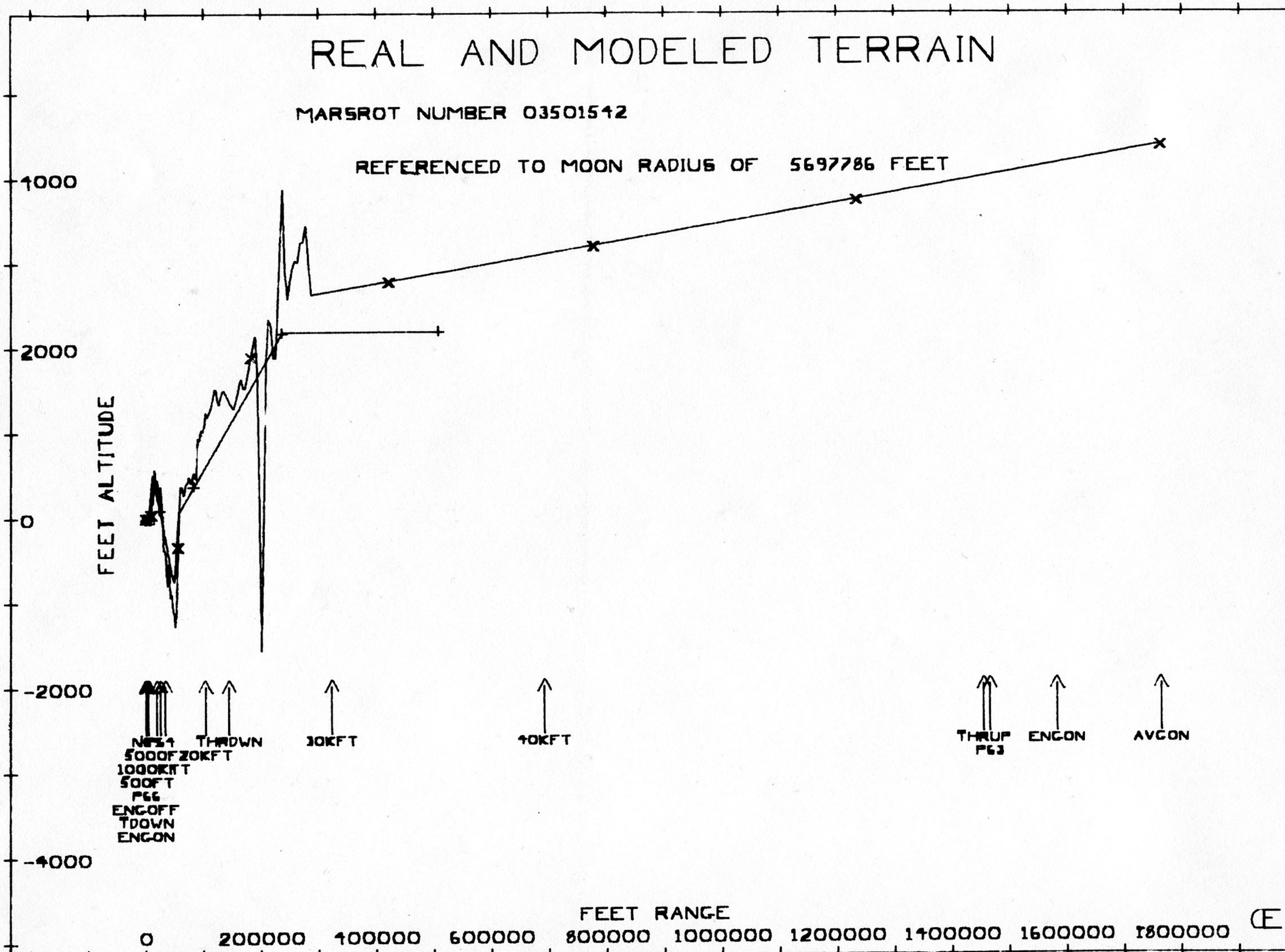


Figure 3B Land 3280 ft. Beyond Nominal Site

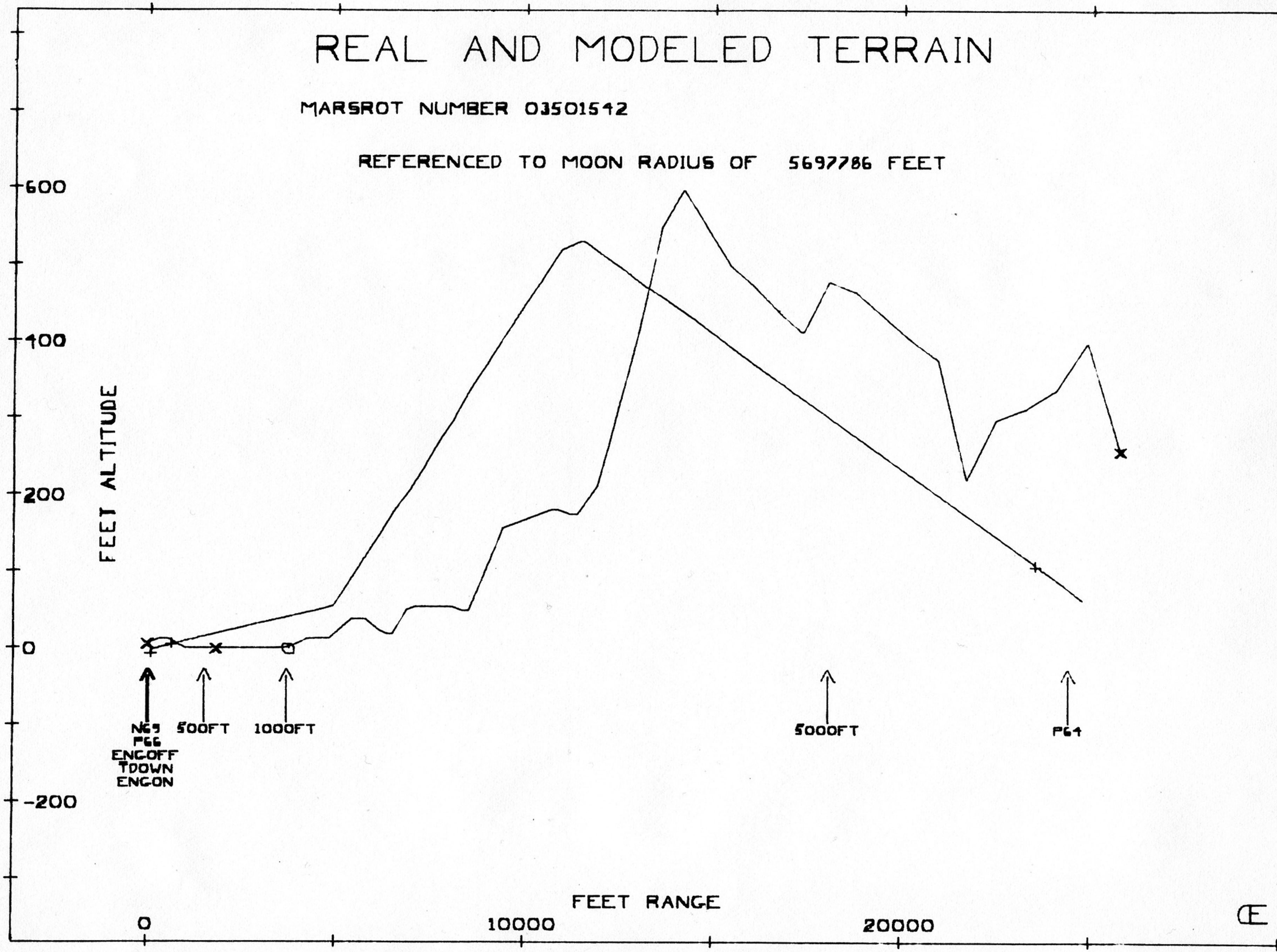


Figure 3C Land 3280 ft. Beyond Nominal Site

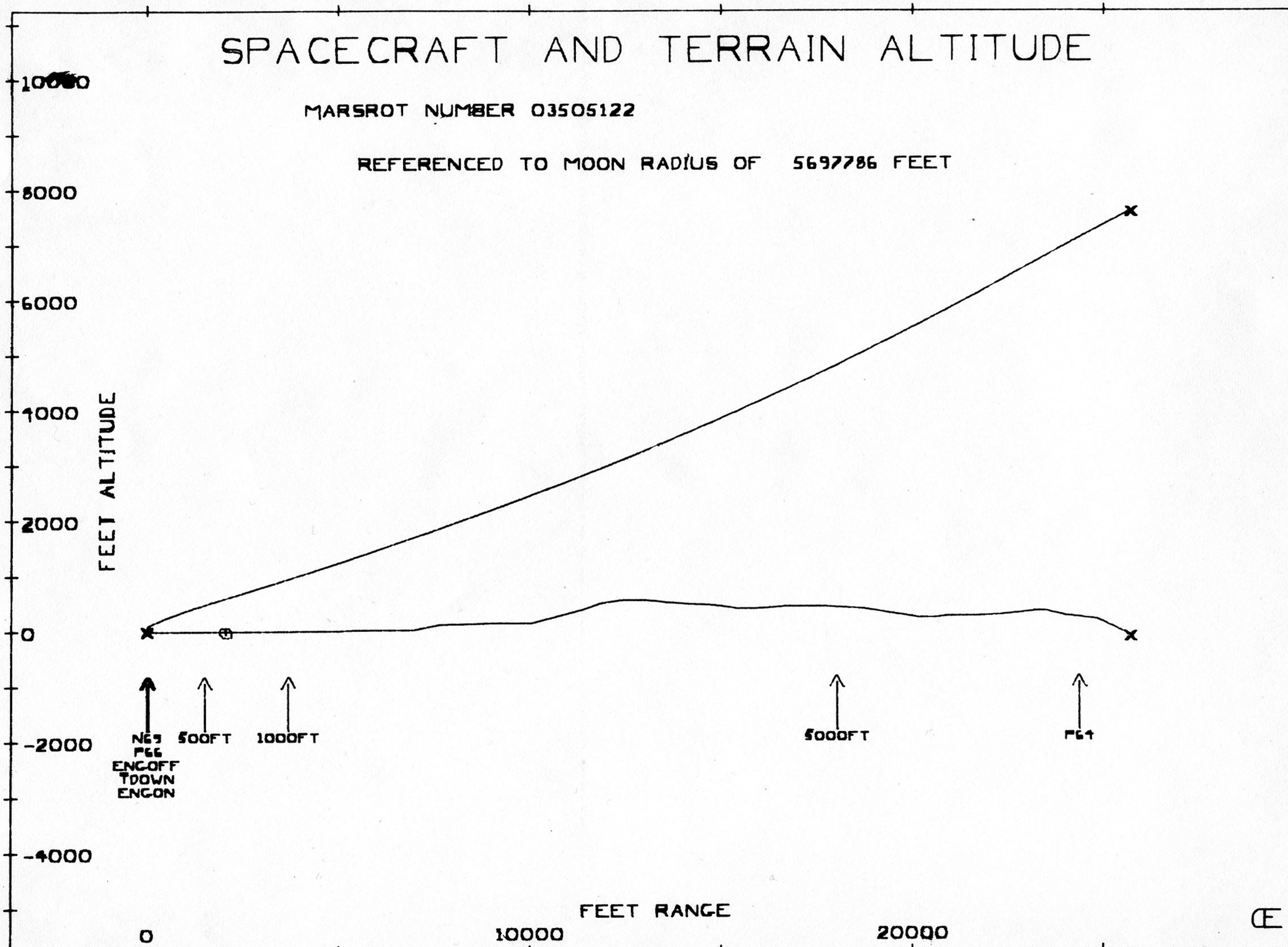


Figure 4A Land 1640 ft. Beyond Nominal Site

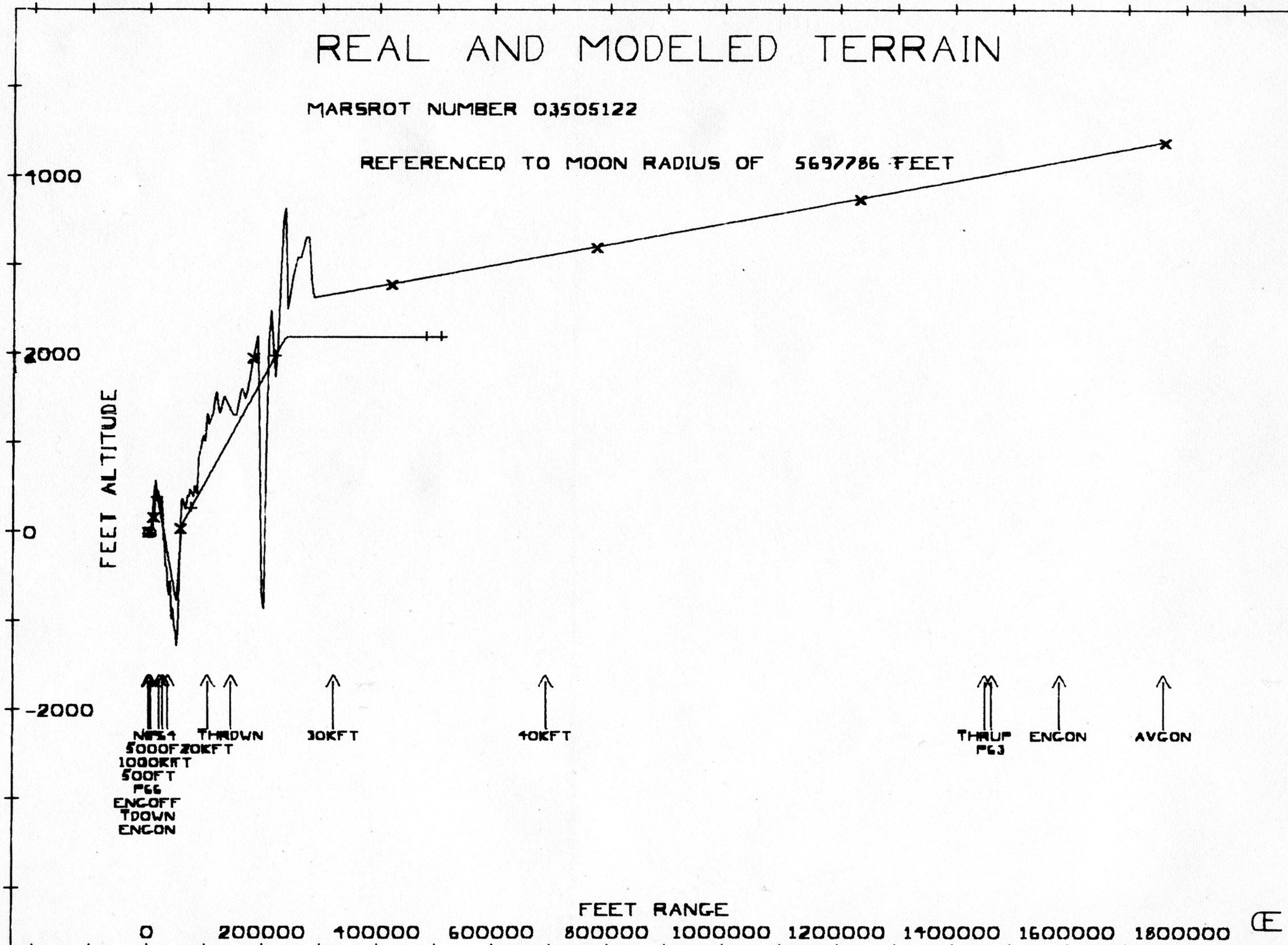


Figure 4B Land 1640 ft. Beyond Nominal Site

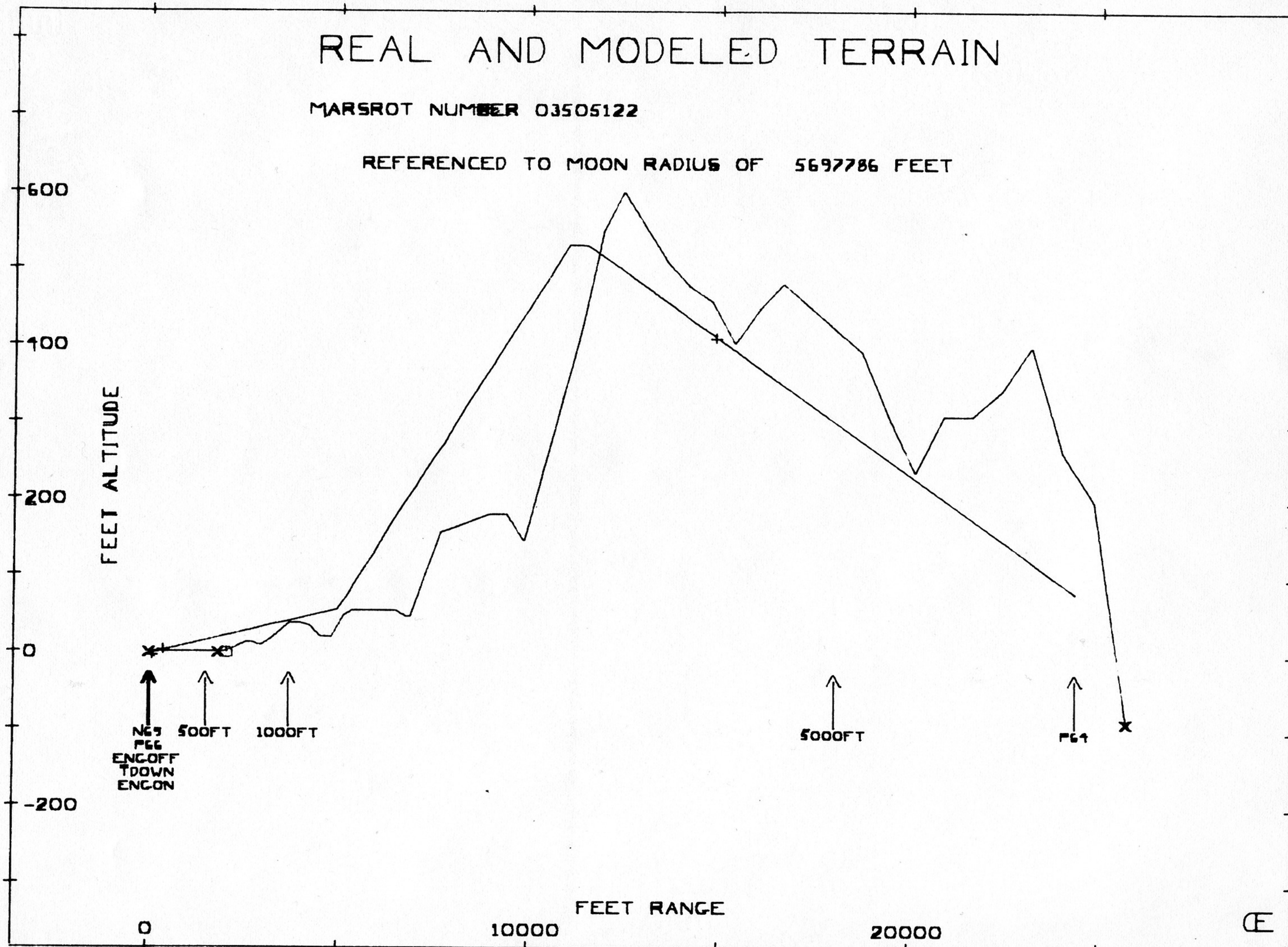


Figure 4C Land 1640 ft. Beyond Nominal Site

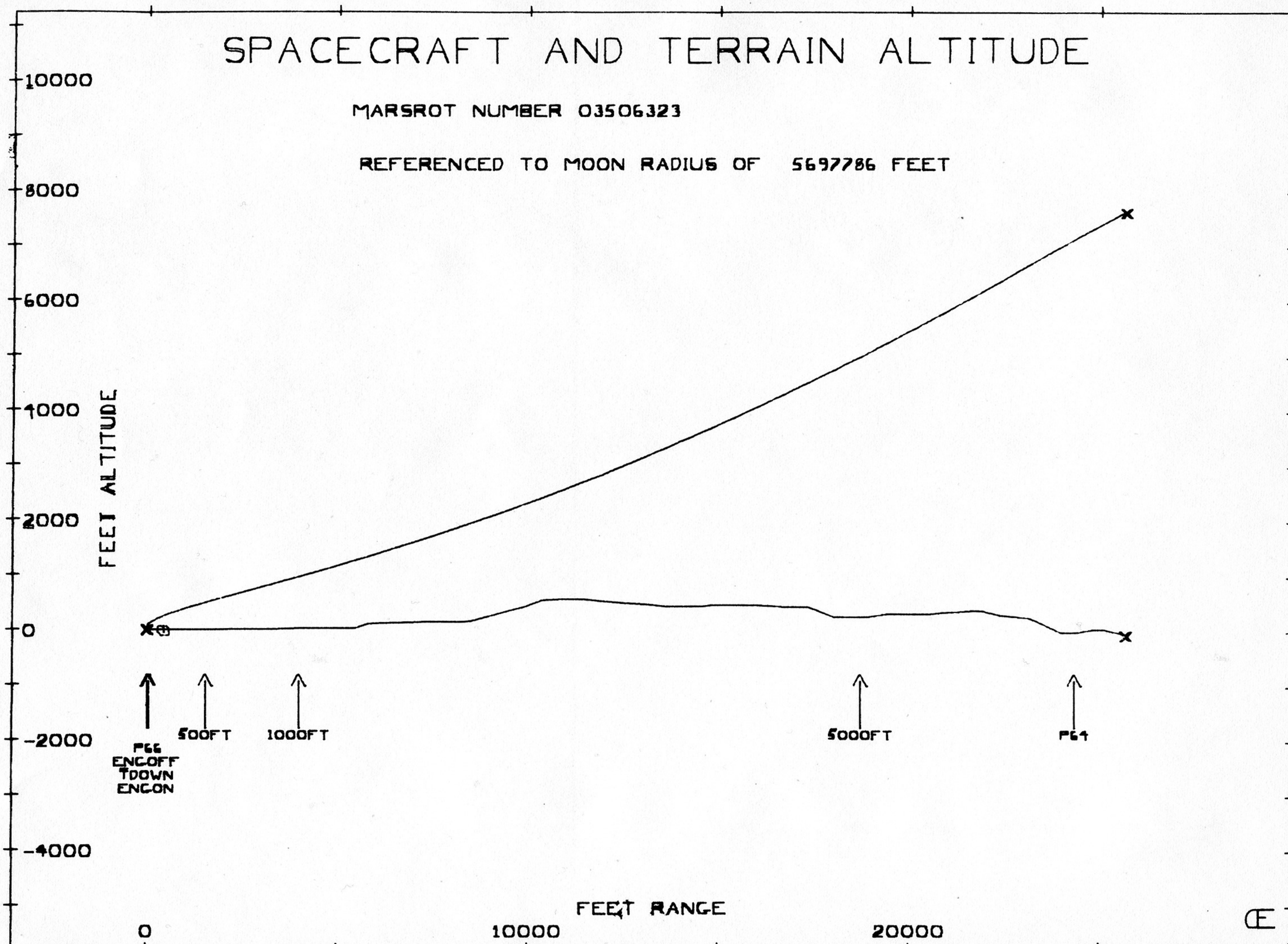


Figure 5A Land at Nominal Site

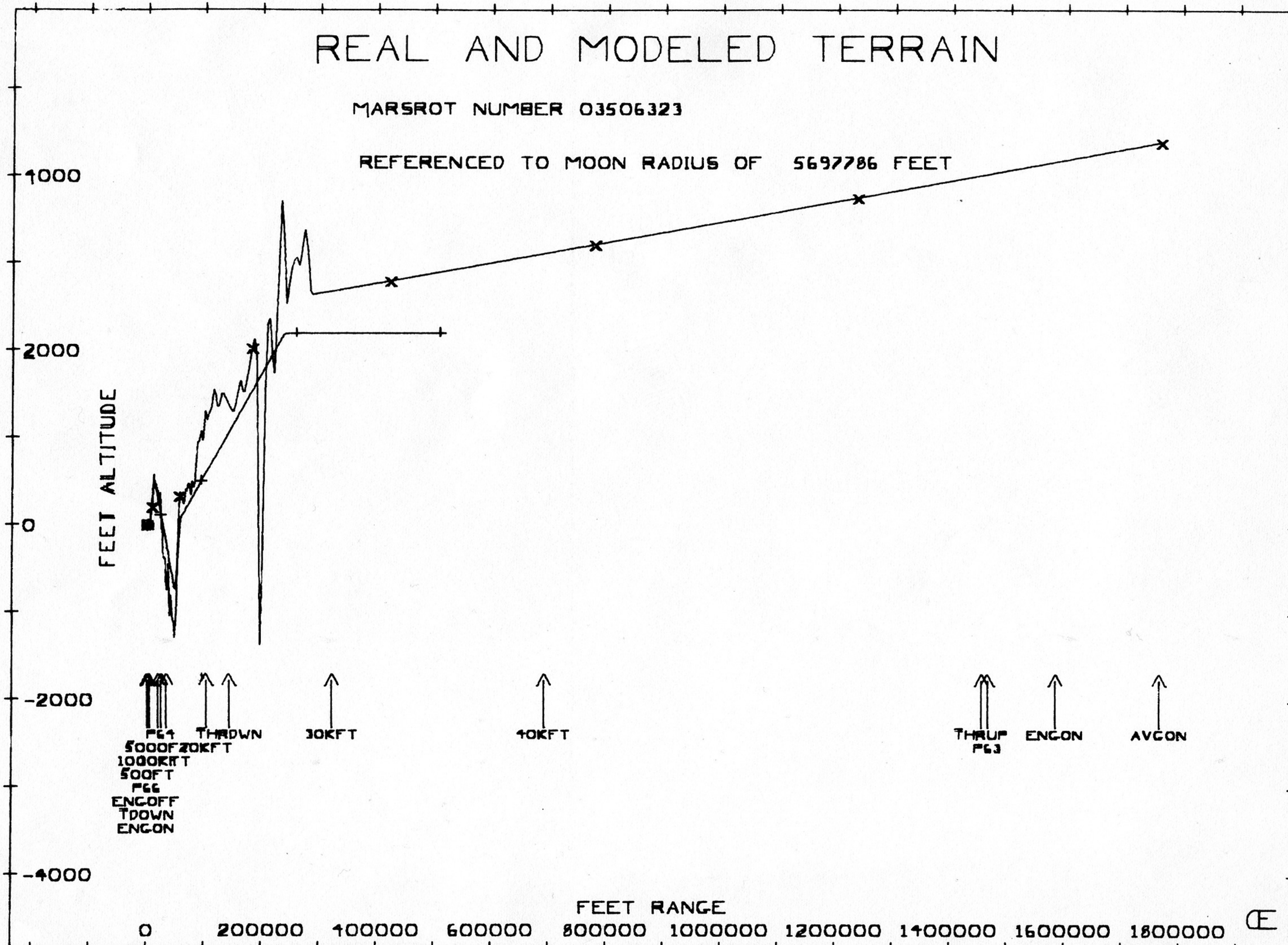


Figure 5B Land at Nominal Site

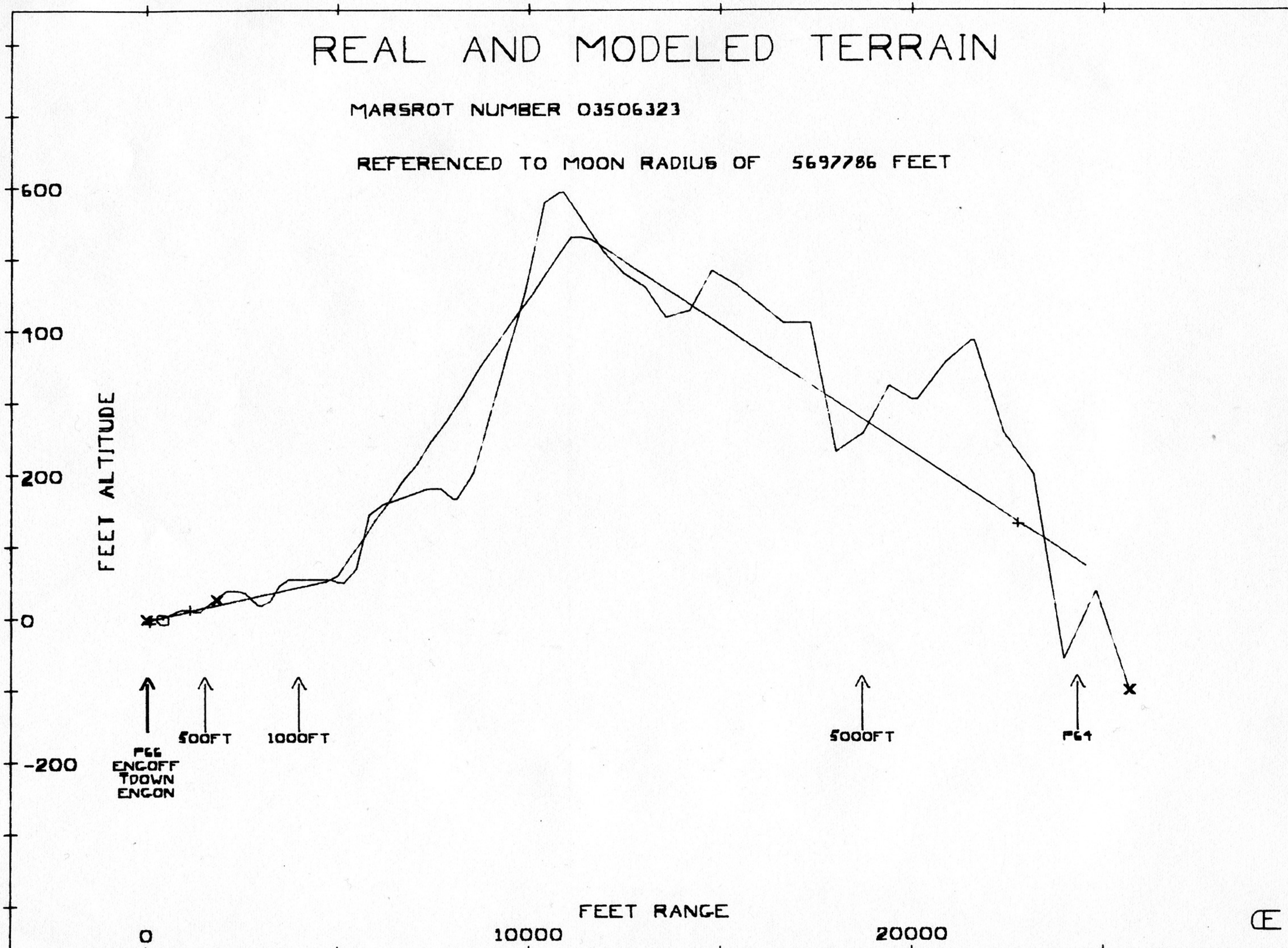


Figure 5C Land at Nominal Site

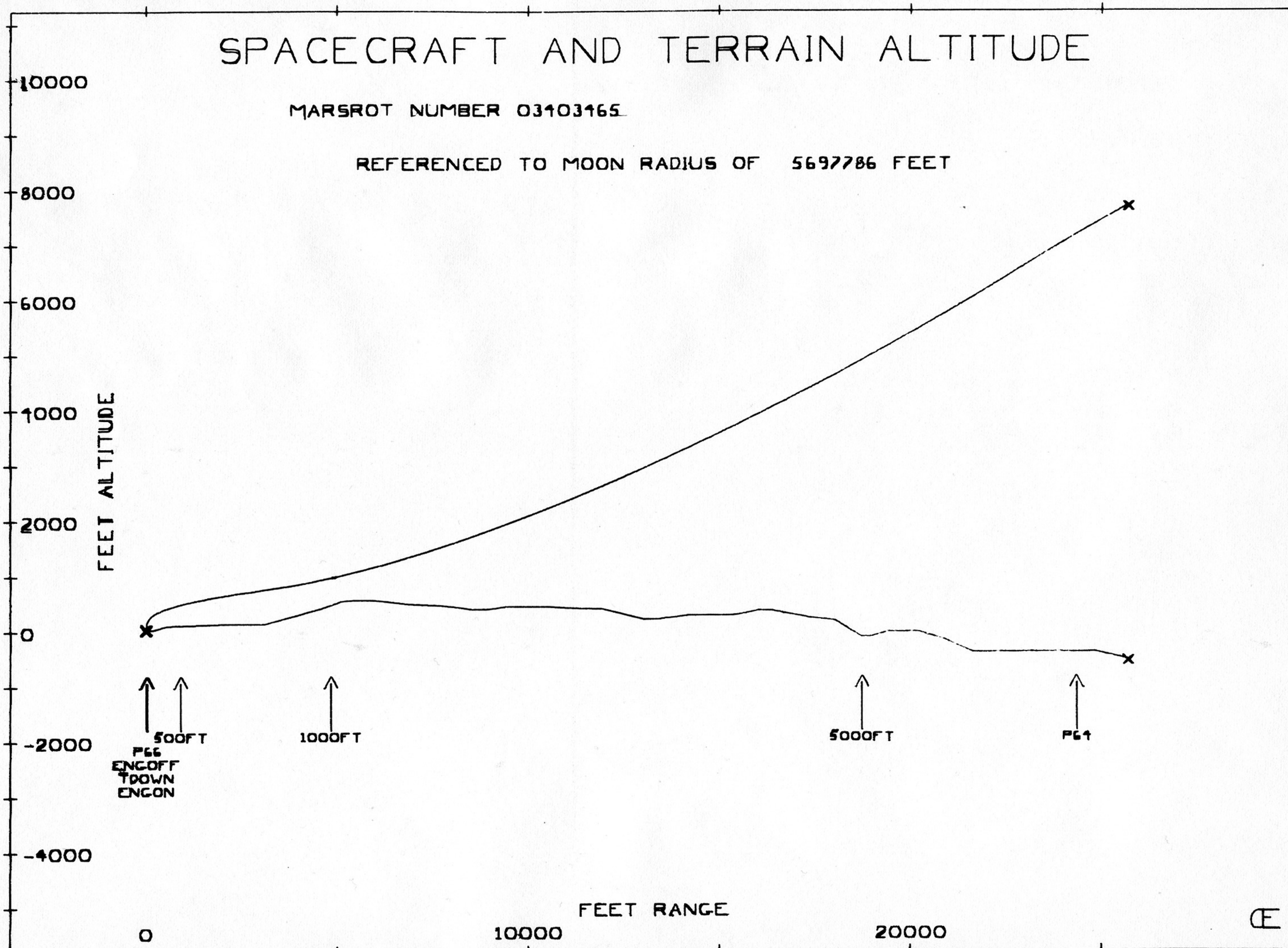


Figure 6A Land 4850 ft. Before Nominal Site

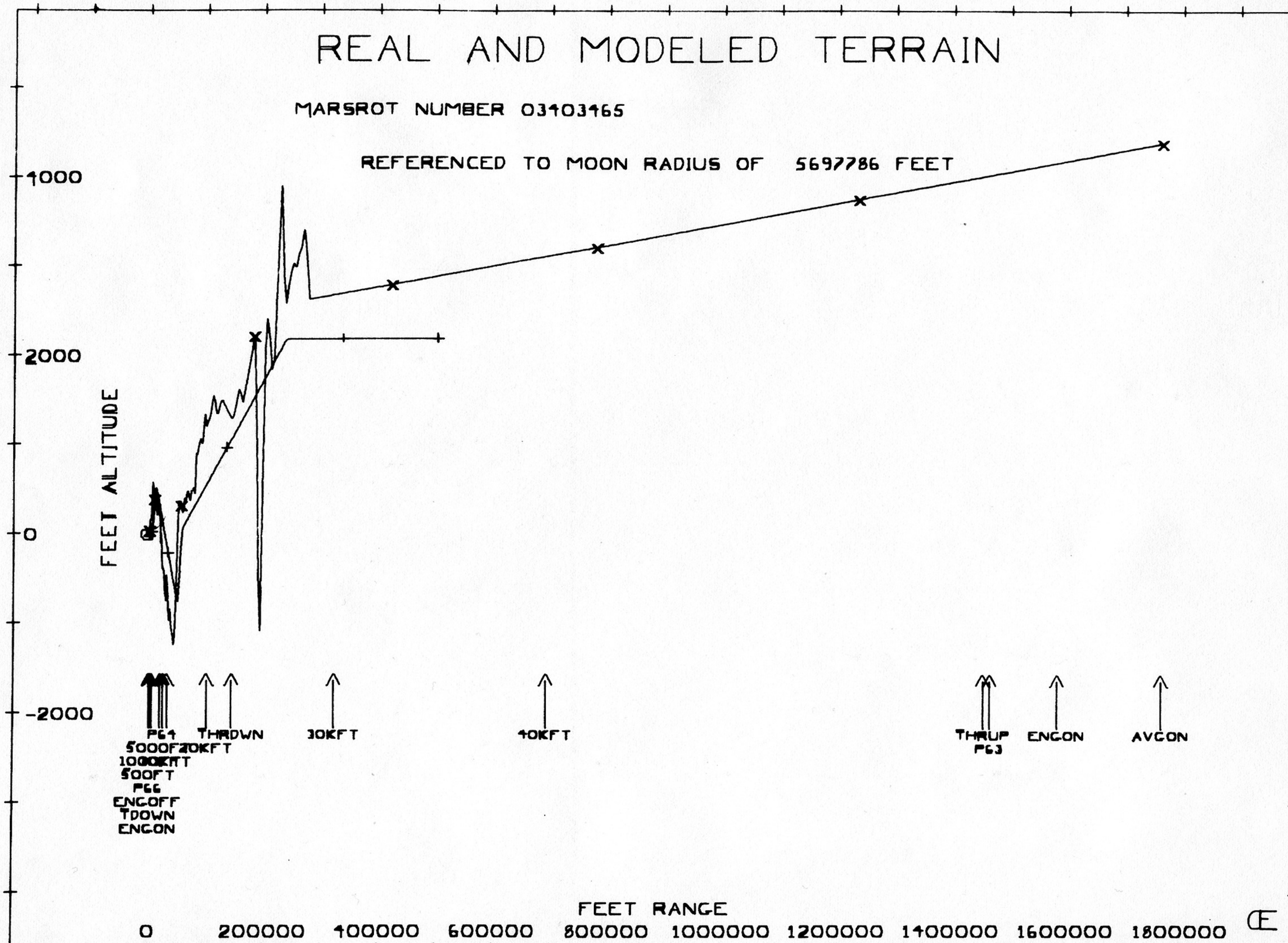


Figure 6B Land 4850 ft. Before Nominal Site

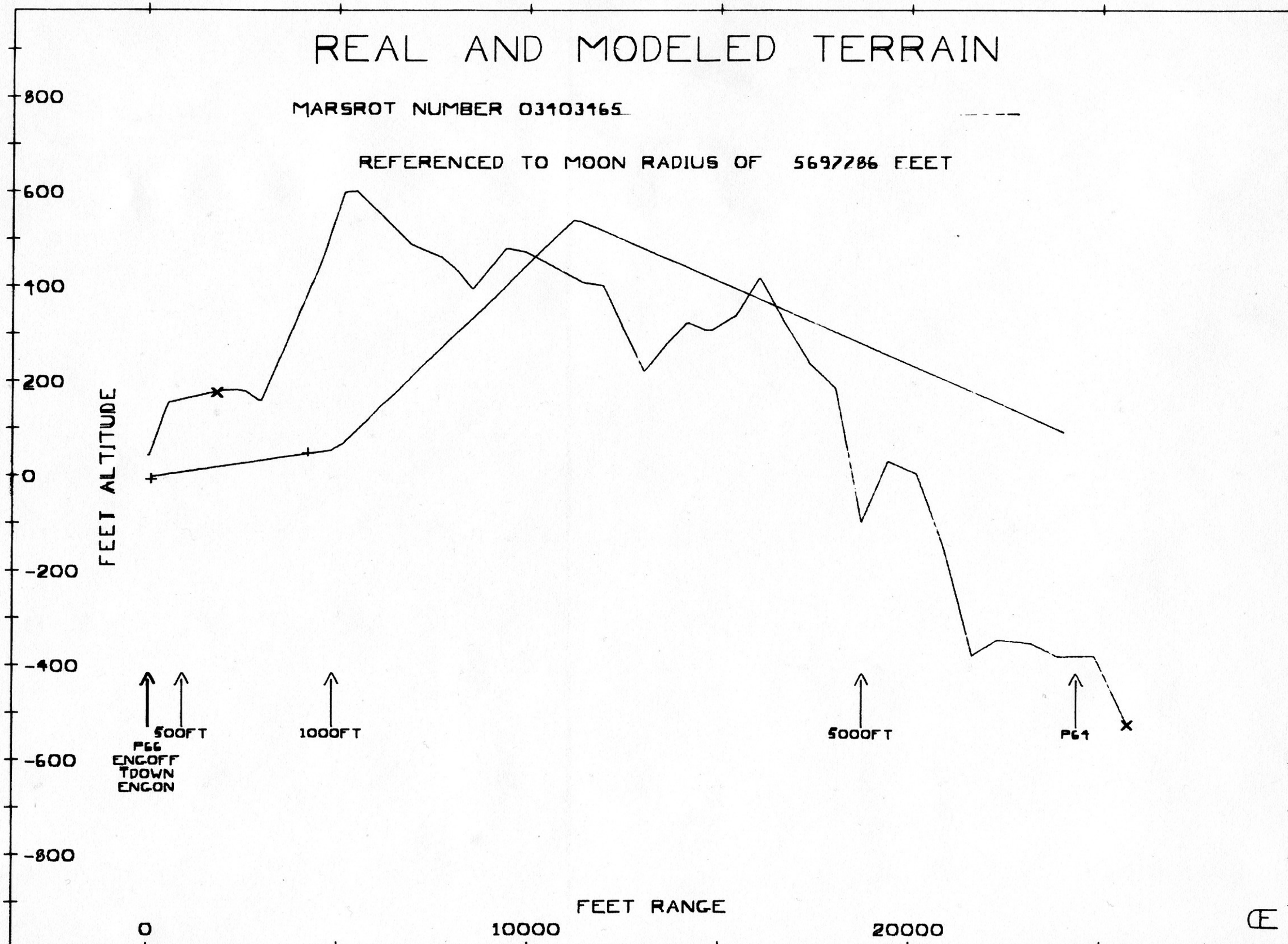


Figure 6C Land 4850 ft. Before Nominal Site

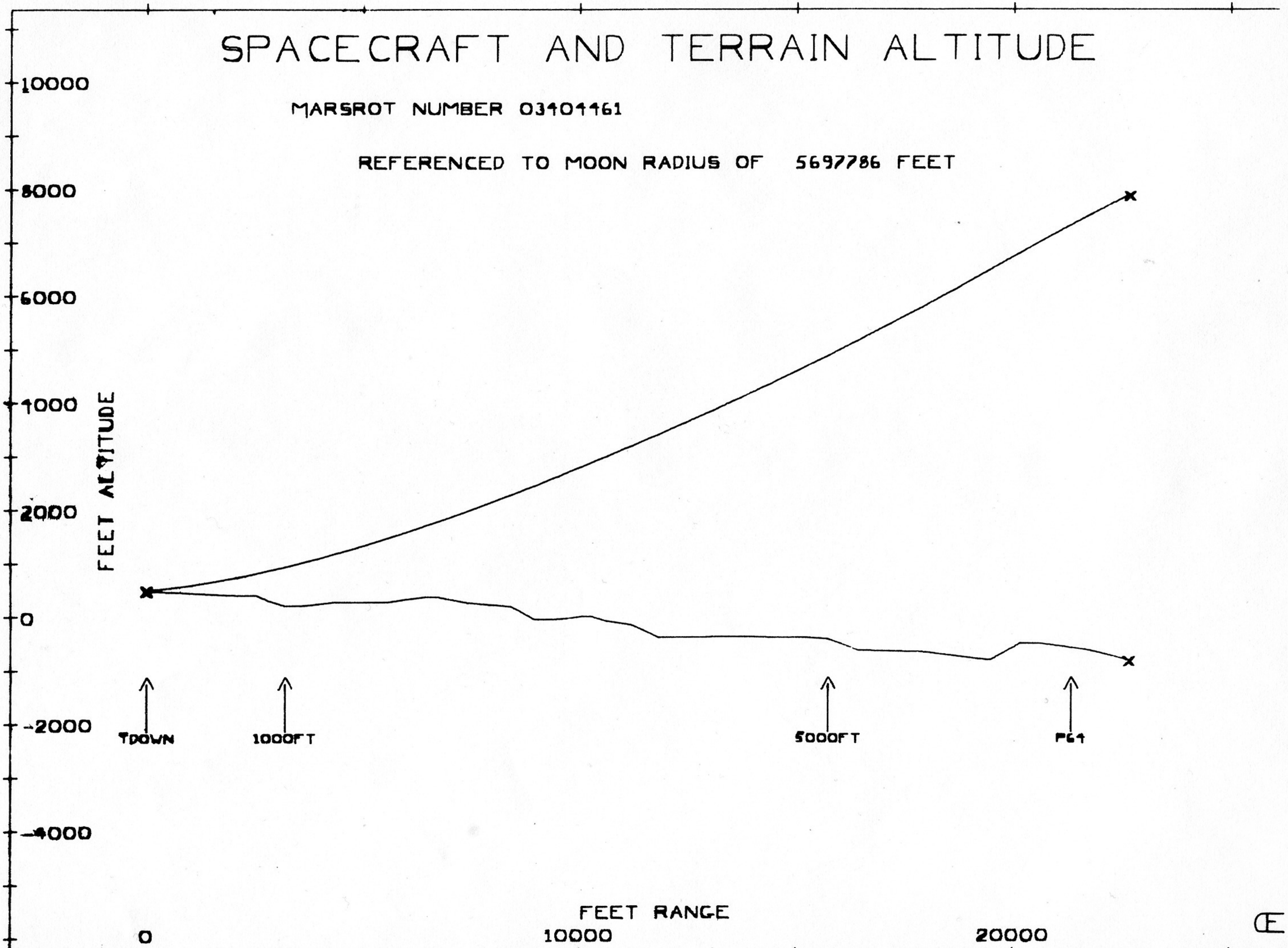


Figure 7A Attempt to Land 11,400 ft. Before Nominal Site

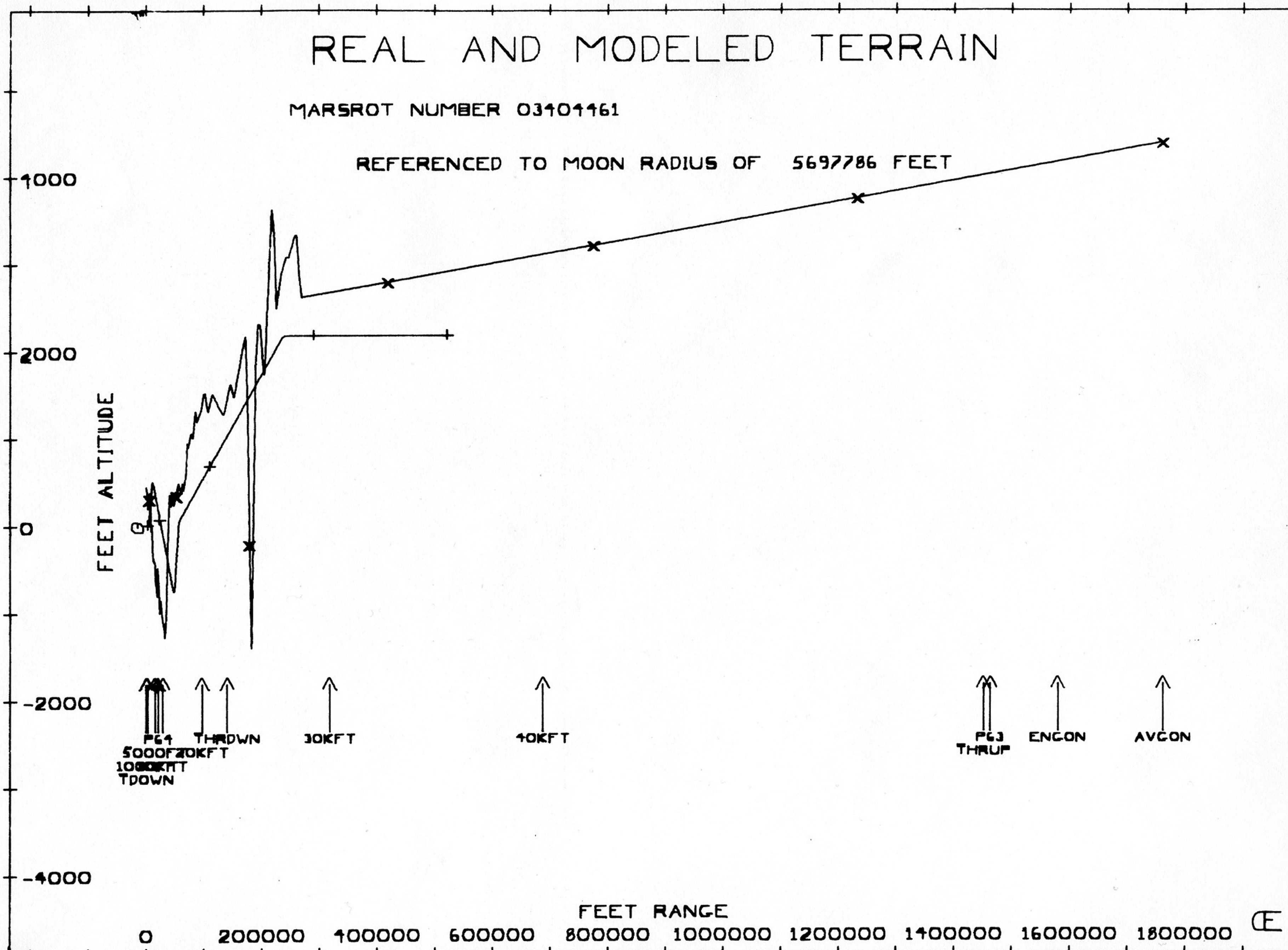


Figure 7B Attempt to Land 11,400 ft. Before Nominal Site

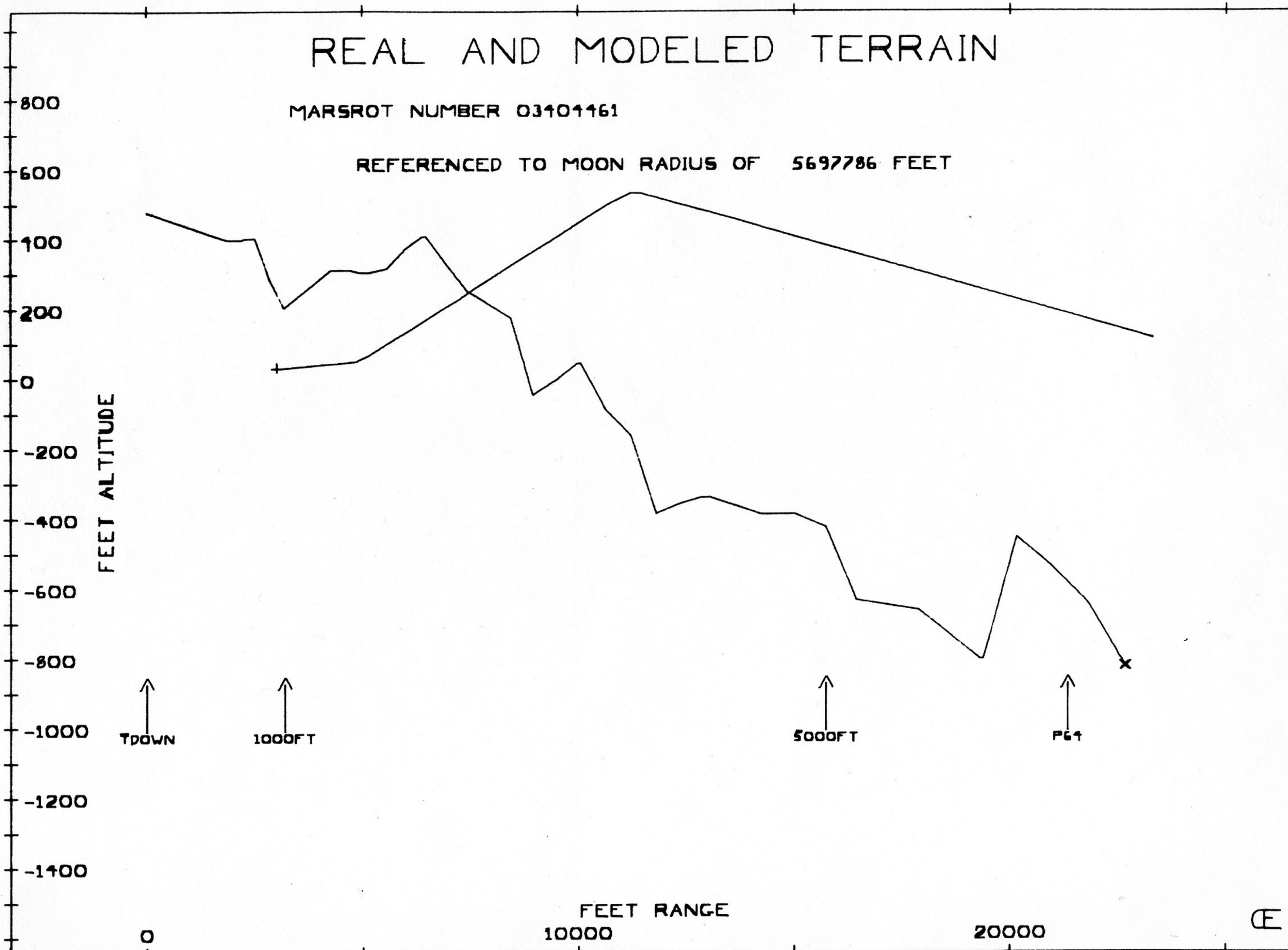
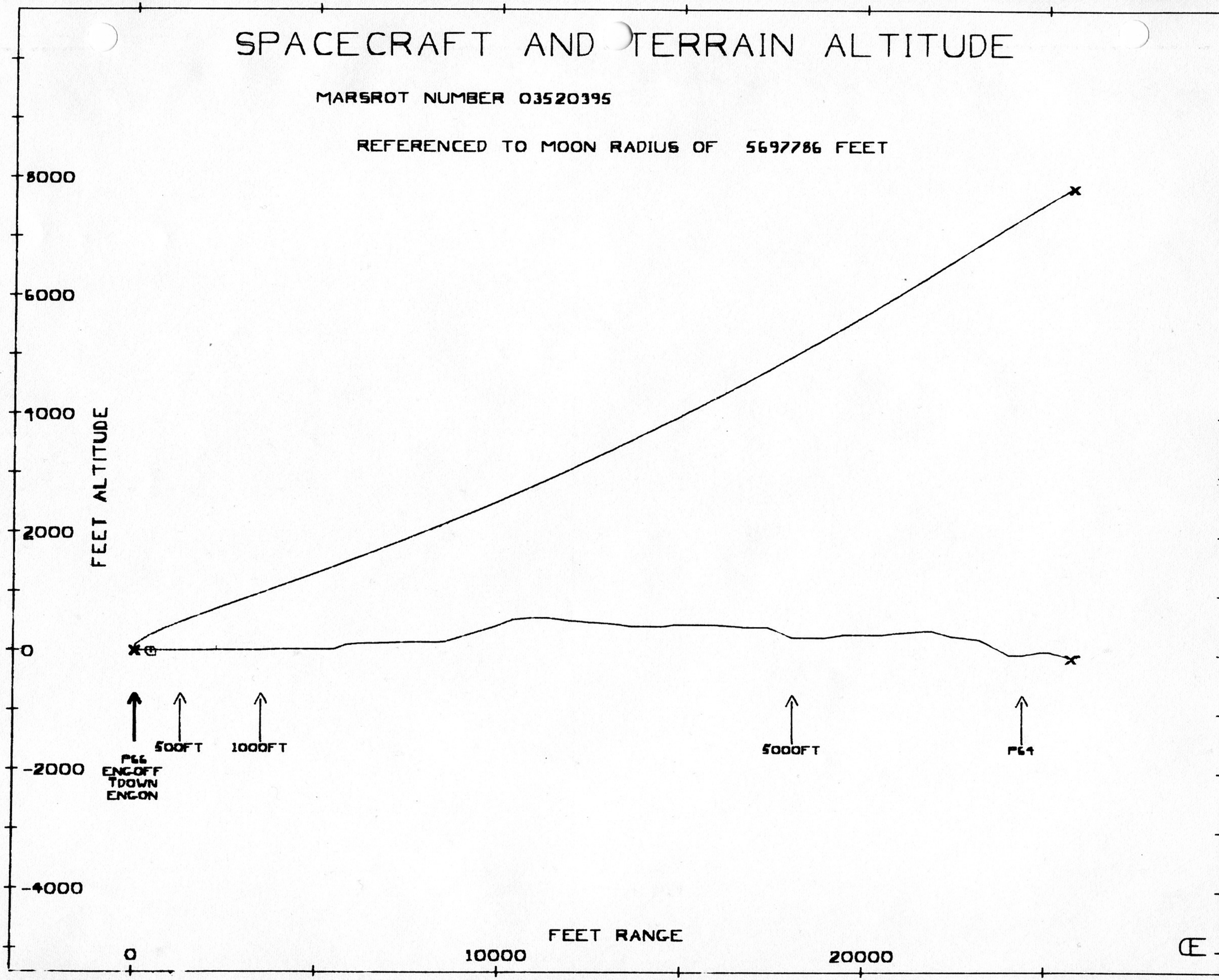


Figure 7C Attempt to Land 11,400 ft. Before Nominal Site



SPACECRAFT AND TERRAIN ALTITUDE
MARSROT NUMBER 03520395
REFERENCED TO MOON RADIUS OF 5697786 FEET
FEET ALTITUDE
8000
6000
4000
2000
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-2000
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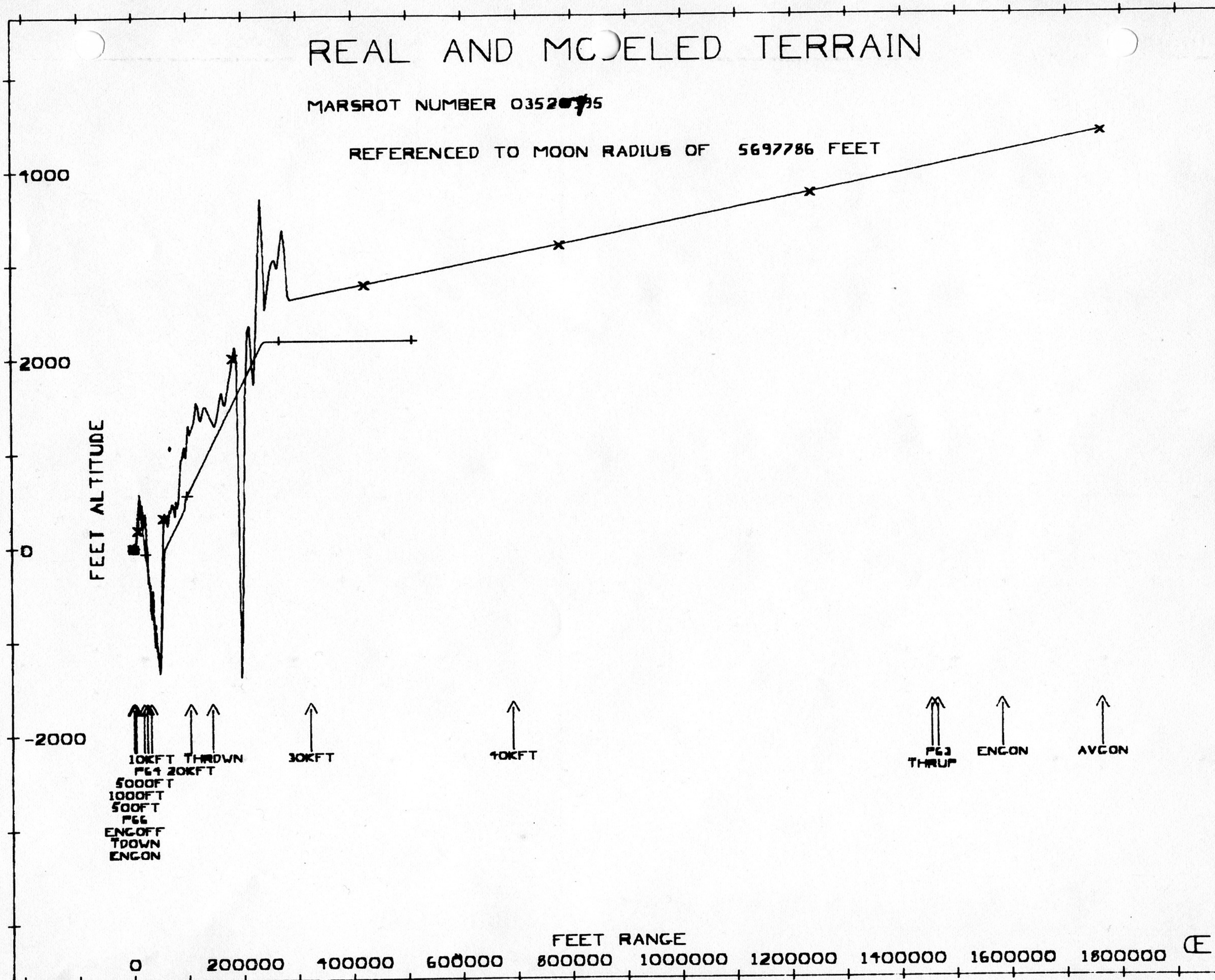
P66
ENGOFF
TDOWN
ENGON
500FT
1000FT
5000FT
P64
FEET RANGE
0
10000
20000



REAL AND MODELED TERRAIN
MARSROT NUMBER 0352
REFERENCED TO MOON RADIUS OF 5697786 FEET
FEET ALTITUDE
1000
2000
0
-2000
10KFT
F64
5000FT
1000FT
500FT
F66
ENGOFF
TDOWN
ENGON
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30KFT
40KFT
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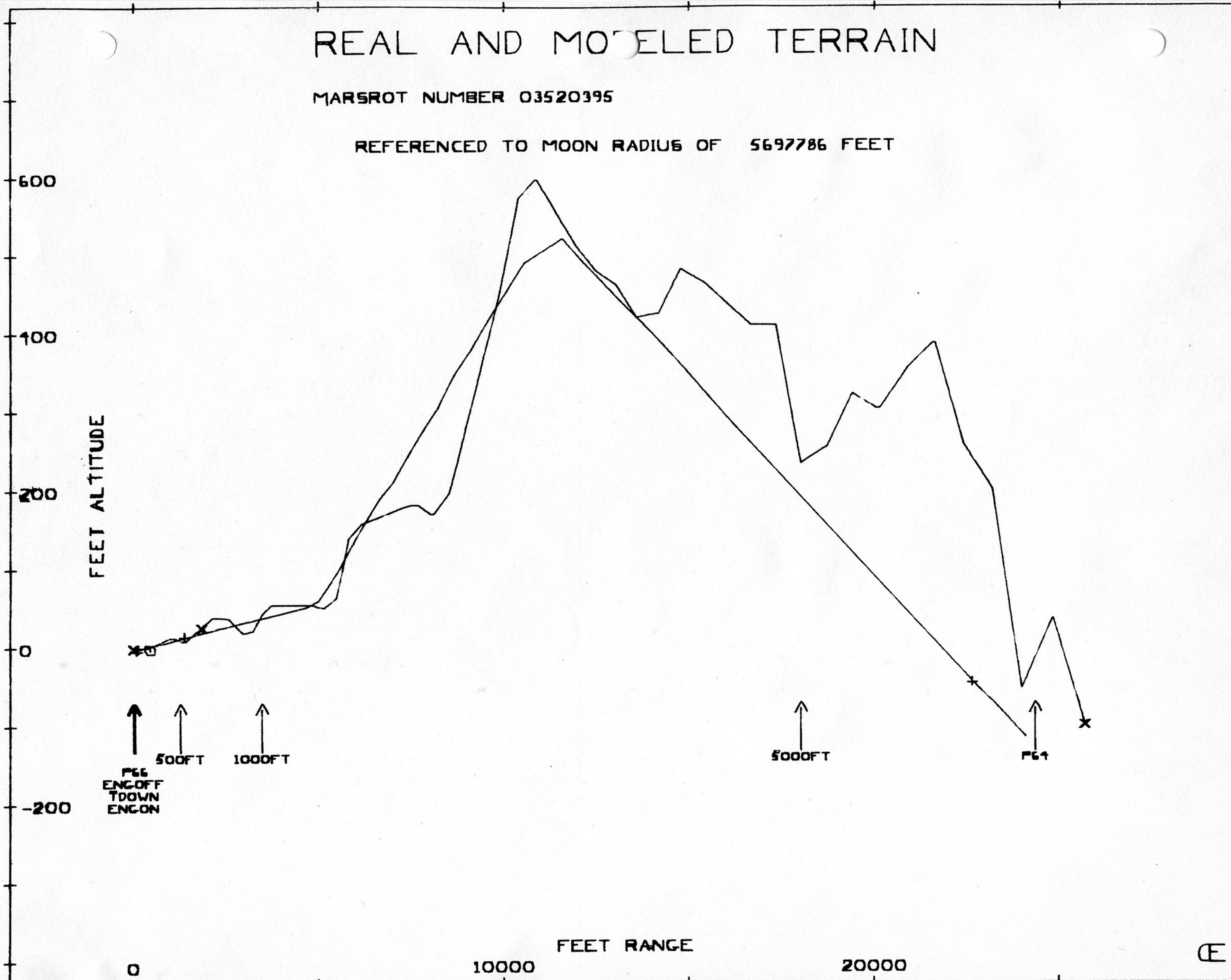
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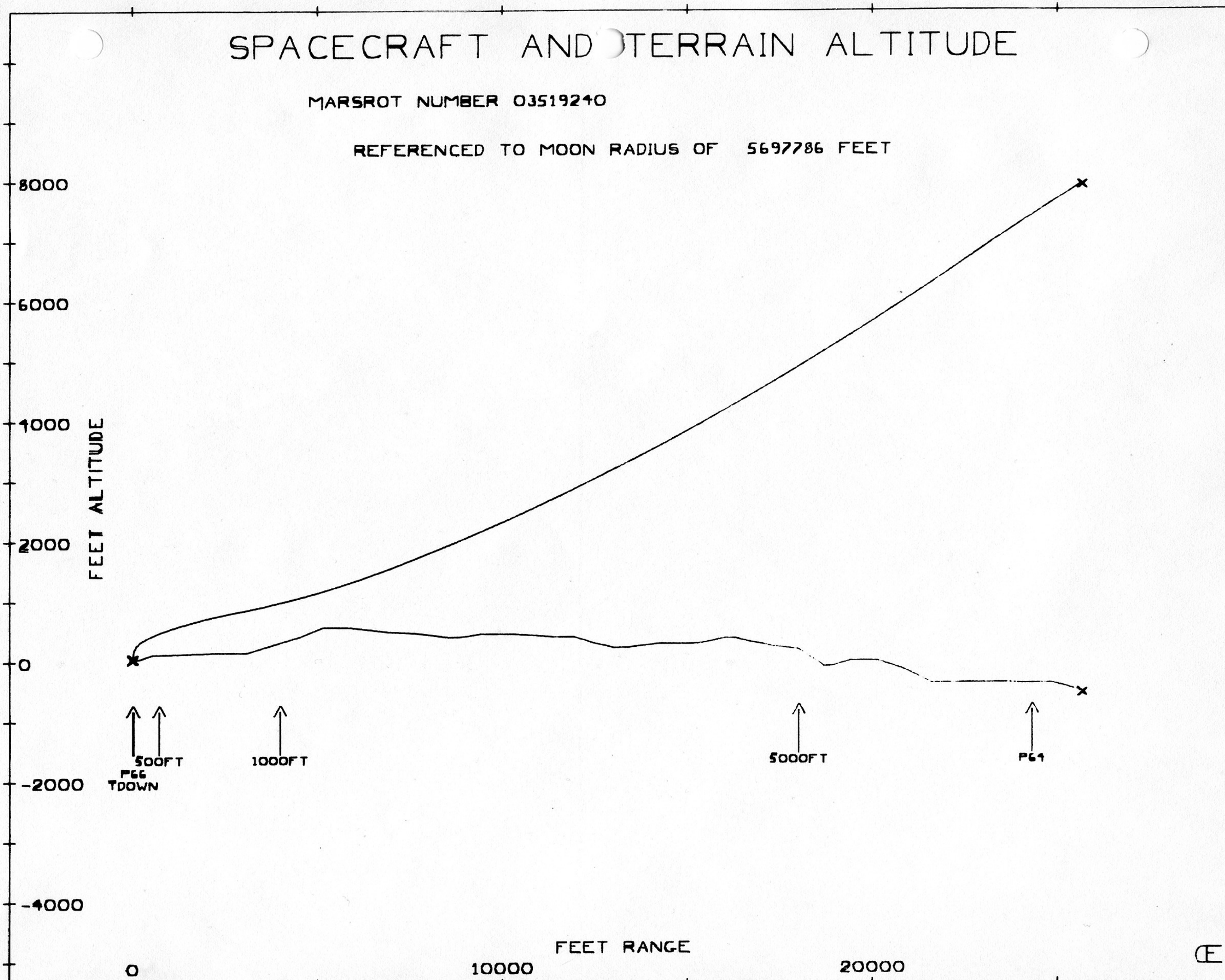
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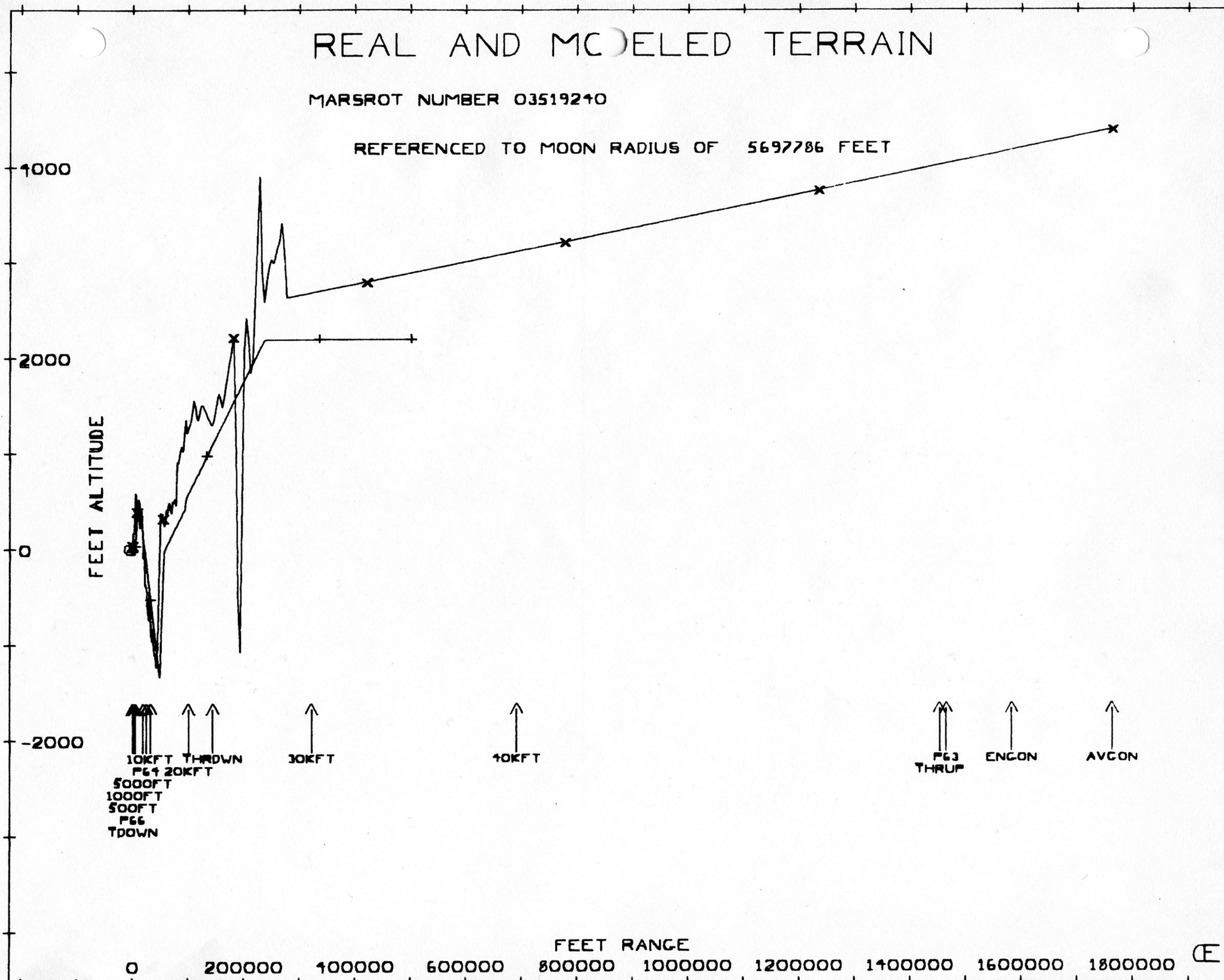

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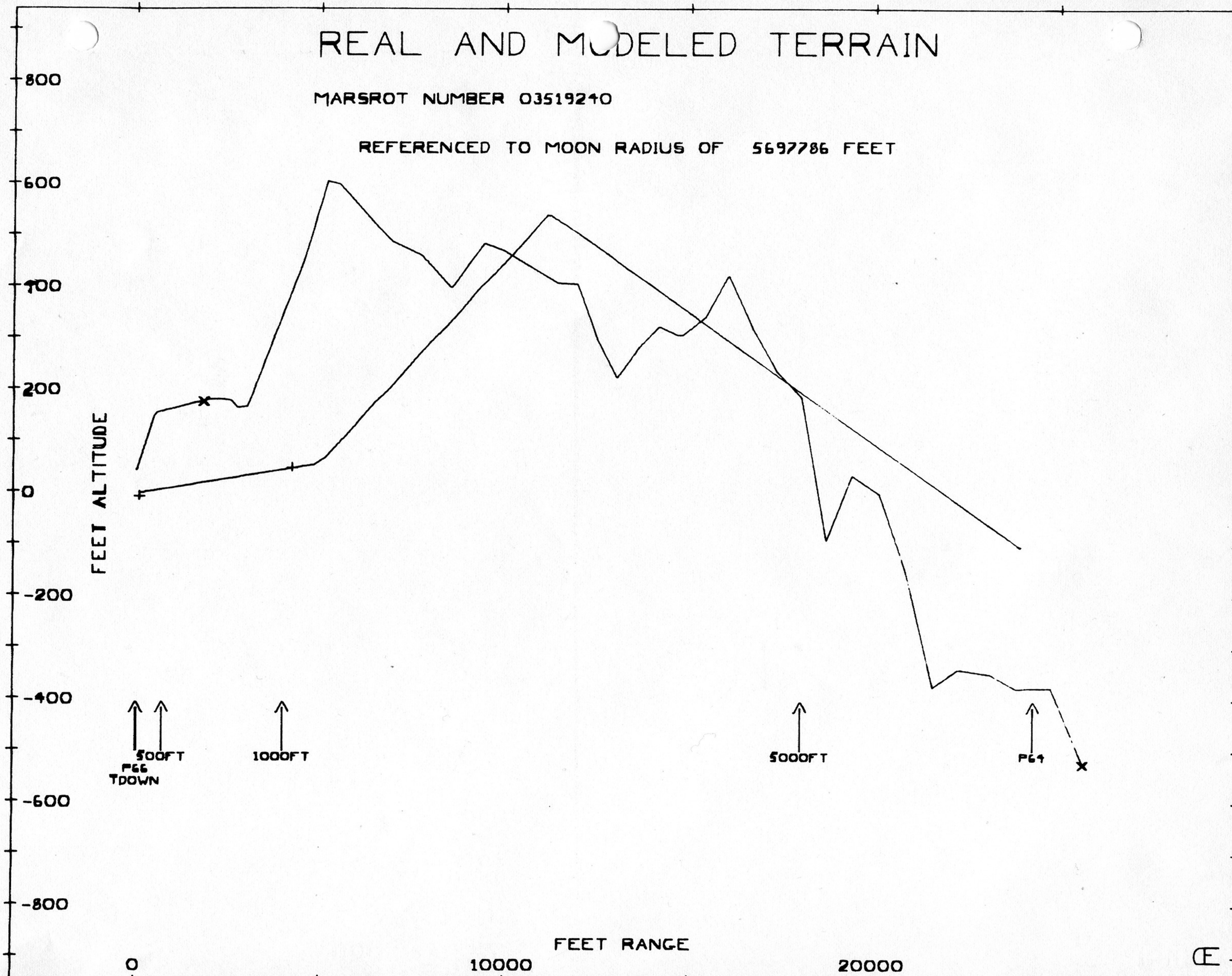
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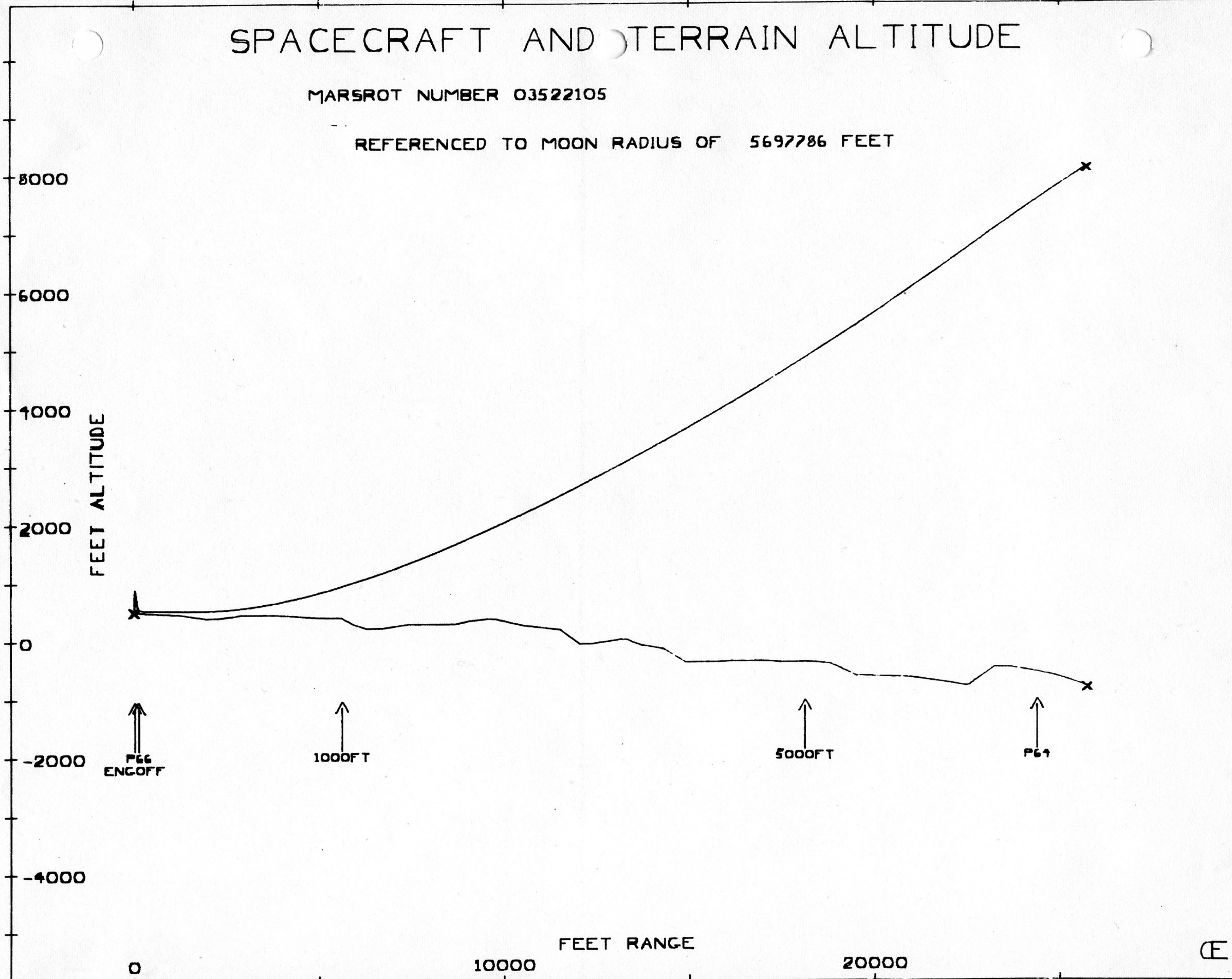
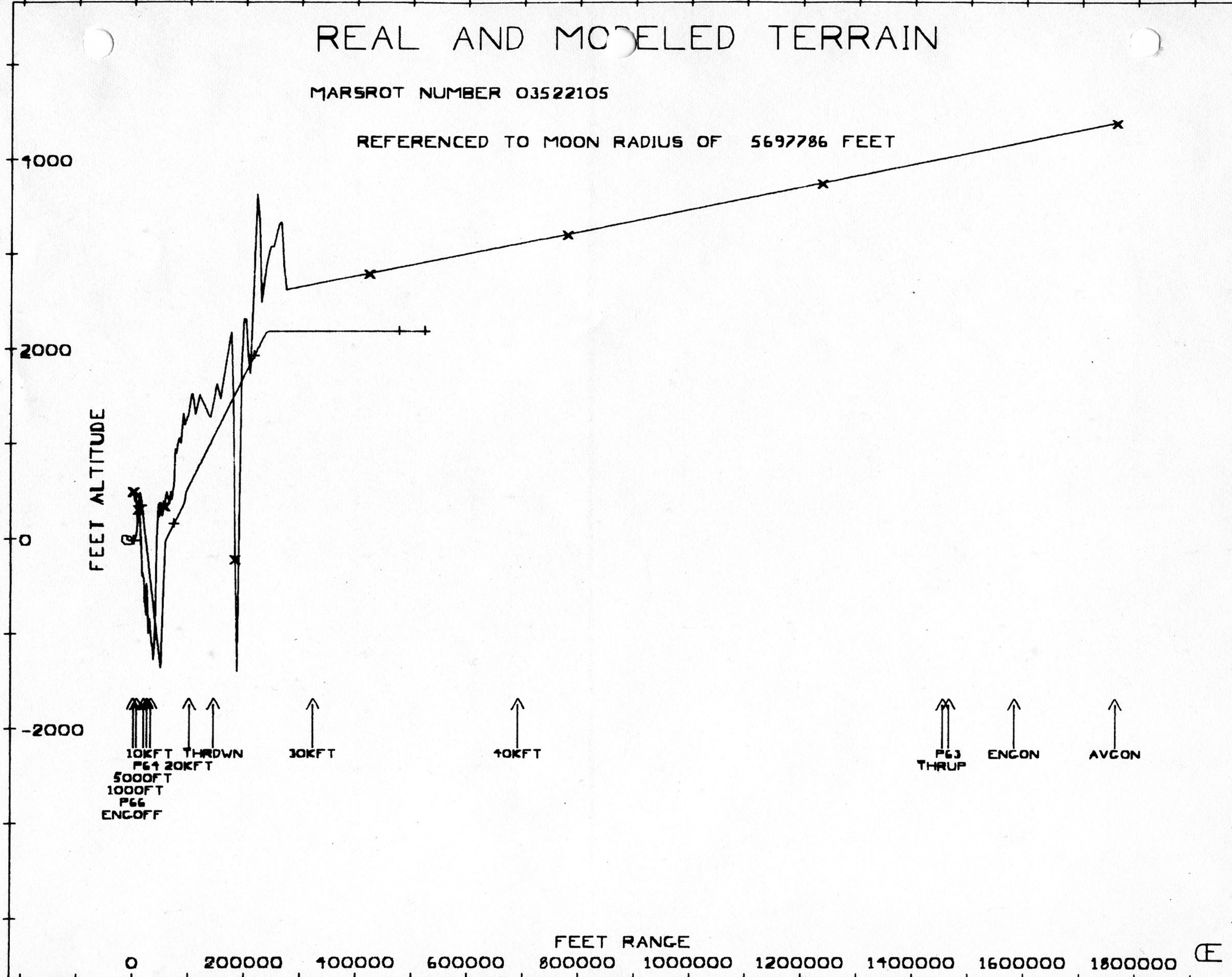


Figure 10A. Corrected Apriori Terrain-Land 11,400 ft. Before Nominal Site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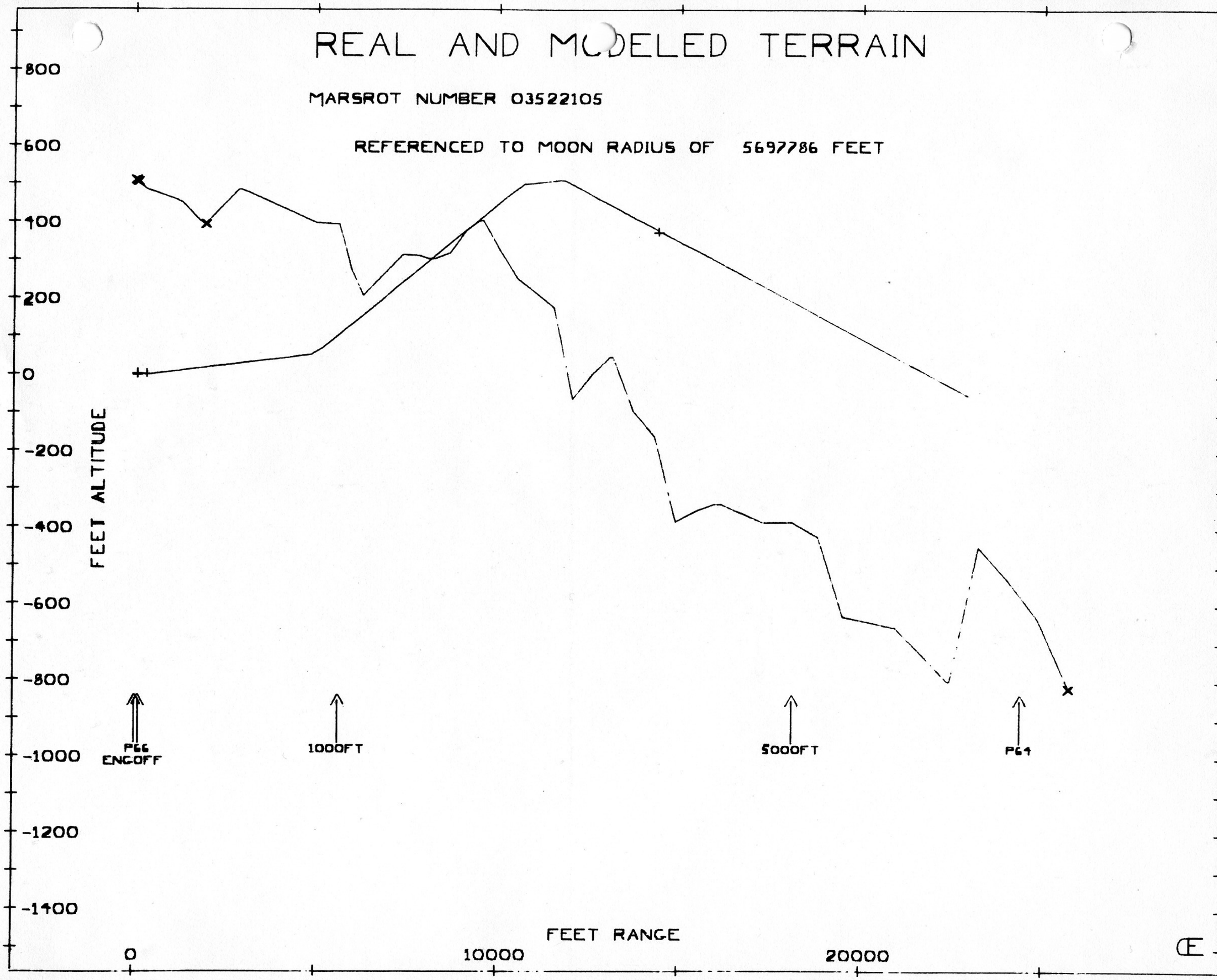
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FEET ALTITUDE
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P64
FEET RANGE
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10000
20000

REFERENCES

1. Apollo 14 (H3) Mission Operational Trajectory Simulator Data Package, FM13 / Mission Planning Support Office Data Management Group, No. 70-FM13-348, September 21, 1970, National Aeronautics and Space Administration, Manned Spacecraft Center.

2. Kriegsman, B.A. and Gustafson, D.E., "Powered Landing-Maneuver Navigation Over Rough Terrain", C.S. Draper Lab 23A Mission Simulation Memo #2-70, February 18, 1970.